Astronomy & Astrophysics manuscript no. richichi
(DOI: will be inserted by hand later)
February 5, 2008

The Calar Alto lunar occultation program: update and new results*

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Received / Accepted

Abstract. We present an update of the lunar occultation program which is routinely carried out in the near-IR at the Calar Alto Observatory. A total of 350 events were recorded since our last report (Fors et al. 2004). In the course of eight runs we have observed, among others, late-type giants, T-Tauri stars, and infrared sources. Noteworthy was a passage of the Moon close to the galactic center, which produced a large number of events during just a few hours in July 2004. Results include the determinations of the angular diameter of RZ Ari, and the projected separations and brightness ratios for one triple and 13 binary stars, almost all of which representing first time detections. Projected separations range from $0\farcs09$ to $0\farcs007$. We provide a quantitative analysis of the performance achieved in our observations in terms of angular resolution and sensitivity, which reach about $0\farcs003$ and $K \approx 8.5$ mag, respectively. We also present a statistical discussion of our sample, and in particular of the frequency of detection of binaries among field stars.

Key words. Astrometry – Occultations – Binaries: close – Binaries: visual

1. Introduction

Among the various methods to achieve high-angular resolution beyond the limits set by atmospheric turbulence and by the telescope diffraction, lunar occultations (LO) stand out for their relative simplicity. LO have been used intensively for investigations of stellar sources for a few decades, and have led to systematic determinations of angular diameters and binary stars. A recent census of LO results was provided by Richichi et al. 2005. In recent years attention and resources are shifting to methods such as long-baseline interferometry (LBI), which offer almost complete freedom of choice in the targets and times of observation, although with much more demanding technical requirements. However, in our opinion LO can still offer a significant scientific contribution with relatively small effort, and attempts to continue routine LO observations should be encouraged. One important advancement in this area has been the recent availability of all-sky near-infrared surveys, such as 2MASS (Cutri et al. 2003) and DENIS (Paturel et al. 2003). Such catalogues have increased by almost an order of magnitude the number of predictions for events observable with 1 m-class telescopes and above.

In this paper, we provide an overview of the data we have accumulated since our last publication on the subject (Fors et al. 2004, F04 hereafter), adding 350 LO events. We present new approaches in data analysis, suited to the automated reduction of large volumes of LO, and we provide details on 11 new binaries and one triple star, 2 known binaries, and one angular diameter determinations. We also discuss the statistics of our sample, with some considera-

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* Based on observations collected at TIRGO (Gornergrat, Switzerland), and at Calar Alto (Spain). TIRGO is operated by CNR–CAISMI Arcetri, Italy. Calar Alto is operated by the German–Spanish Astronomical Center. Table 5 is only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/

tions on the detection of binaries in random observations of field stars.

2. Observations, data handling and data reduction

Most of the observations reported here were carried out with the 1.5 m telescope of the Observatorio Astronómico Nacional in Calar Alto (Spain). On two occasions, we used the 3.5 m and 2.2 m telescopes of the Centro Astronómico Hispano-Alemán, located at the same site. Among the present results we have included also two earlier observations obtained at the TIRGO 1.5 m telescope, for which a detailed re-analysis has shown a positive binary detection. The above telescopes, the associated instrumentation and the filter bandpasses used for LO work have been described elsewhere (Richichi et al. 1996, F04). Concerning the K-filter of the MAGIC cameras used at 1.5 m and 2.2 m telescopes of Calar Alto, we have determined an improved, accurate transmission curve at operating temperature, and applied it in all relevant cases. For this purpose we have used the same MAGIC camera in the laboratory, taking exposures with and without the filter, using the same resin-replica grism used for astronomical observations at liquid nitrogen temperature. As a light source we employed a source without significant emission in the J band, thus avoiding contamination of short-wavelength light from a different order. For the observation of the very bright star RZ Ari we employed a narrow band filter, with $\lambda_0 = 2.26\mu$m and $\Delta\lambda = 0.06\mu$m.

Observations were carried out during eleven observing runs at the Calar Alto Observatory over a period of two years, as detailed in Table 1. On average, each run consisted of a few nights allocated in periods of crescent Moon close to full phase, in order to maximize the number of occultations of field stars and observe disappearances rather than reappearances. On two occasions (runs G and H), very short runs were allocated to follow up passages of the Moon close to the galactic center and over the Taurus star-forming regions, respectively. Note that three runs were completely devoid of results due to weather. The two earlier results from TIRGO are collectively grouped as run A, although their respective observations were collected at different dates in 2001. Details of the 350 recorded events and the characteristics of the corresponding objects can be found in Table 5, available only on-line. Here we show an excerpt in Table 2, which contains the details of the sources explicitly mentioned either for a positive result or for other comments. The format of this table is similar to the one used in F04. In column (3), the codes T, CB and CC are for the TIRGO telescope equipped with a fast InSb photometer, and for the Calar Alto 1.5,m and 2.2 m telescopes equipped with MAGIC cameras, respectively.

The availability of near-IR all-sky surveys has represented a major step forward in the possibilities of LO investigations, especially at medium and large-sized telescopes. Roughly speaking, a 1.5 m telescope equipped with an InSb fast photometer can record LO events with millisecond time sampling and signal-to-noise ratio (SNR) above unity for sources having magnitudes K$\lesssim$7 (Richichi et al. 1996). An instrument based on the fast readout of a subwindow of an array detector can add more than one magnitude in sensitivity (F04). Moving to larger telescopes brings gain in sensitivities which are essentially, for moderate lunar phases and faint sources, proportional to the area of the telescope (Richichi 1996). While these guidelines are obviously strongly dependent on a number of instantaneous parameters, they show that LO observations can be adequately recorded on sources with magnitudes as faint as K$\approx$10. Until recently, no comprehensive coverage of the near-IR sky was available. The Two Micron Sky Survey (TMSS, Neugebauer & Leighton 1969) was incomplete in declination and only extended to K$\lesssim$3. In the past, LO predictions were compiled by the present authors using a variety of other catalogues. Even a very rich run would consist of about 10-20 sources per night at most. We have now implemented the 2MASS survey (Cutri et al. 2003) in our predictions, and the number of events observable has jumped up by very large factors. A typical night would offer in excess of 100 sources close to maximum lunar phase. Even more dramatic are the improved conditions for special events. For example, on the occasions of passages of the Moon in crowded regions near the Galactic Center (see Sect.3.8), thousand of events would be easily accessible to a medium-sized telescope over few hours. Table 3 lists some statistics for such events in the near future. In this regime, the number of events effectively observable will depend on the overheads of telescope pointing, instrument operation and data storing.

Table 1. Observing runs

Run	Telescope	Dates	Nights	# LO
A	TIRGO 1.5m	Oct, Nov 01	2	2
B	CA 1.5m	Feb 03	5	0
C	CA 1.5m	Nov 03	5	9
D	CA 1.5m	Dec 03	5	0
E	CA 1.5m	Feb 04	6	29
F	CA 1.5m	Mar 04	7	3
G	CA 2.2m	Jul 04	0.5	54
H	CA 3.5m	Oct 04	1	0
I	CA 1.5m	Nov 04	6	45
J	CA 1.5m	Dec 04	5	7
K	CA 1.5m	Jan 05	5	105
L	CA 1.5m	Feb 05	5	96
		Total	53.5	350

Table 3. Statistics of three passages of the Moon in the Galactic Center (GC) region in 2006, as predicted for the Calar Alto Observatory to the limit $K \leq 8.5$ mag.

Date	Start (UT)	End (UT)	Minimum GC approach	Number of LO
11 June	21:01	02:46	1.°95	2899
9 July	20:31	01:48	4.°74	1586
5 August	19:03	23:29	0.°88	2315

Table 2. List of selected occultation events and of the circumstances of their observation

(1) Source	(2) Date UT	(3) Tel.+ detector	(4) D ″	(5) Δt ms	(6) τ ms	(7) V mag	(8) K mag	(9) Sp.	(10) Dist. pc
SAO 164567	25-10-01	T	21	3.0	3.4	7.4	3.2	K5III	278
SAO 110325	28-11-01	T	21	2.0	2.4	6.4	4.1	K0	147
SAO 80310	03-03-04	CB	7	8.5	3.0	6.9	5.6	F8	35
SAO 80764	01-04-04	CB	7	8.4	3.0	7.8	4.0	K2	1429
SAO 185661	28-07-04	CC	5	8.4	3.0	9.9	5.9	K5	
IRC -30319	28-07-04	CC	5	8.4	3.0	8.8	1.8	K2	
17454891-2809333	28-07-04	CC	5	8.3	3.0		6.1		
SAO 164601	18-11-04	CB	7	8.6	3.0	6.2	5.7	A0m...	110
SAO 165154	19-11-04	CB	7	8.4	3.0	9.0	6.2	K1III	
SAO 109617	22-11-04	CB	7	8.4	3.0	8.2	5.5	K2	21
SAO 110089	23-11-04	CB	7	8.4	3.0	8.5	6.7	K0	47
SAO 92659	23-11-04	CB	7	8.5	3.0	5.9	5.1	F2Vw	43
RZ Ari	18-01-05	CB	7	8.4	3.0	5.8	-0.9	M6III	124
SAO 76214	19-01-05	CB	7	8.5	3.0	8.2	5.4	K0	
LH 98-106	19-01-05	CB	7	8.5	3.0	7.3	6.0	F5	37
DL Tau	20-01-05	CB	7	8.4	3.0	13.6	8.0	GV:e...	
GN Tau	20-01-05	CB	7	8.5	3.0	15.1	8.1	M2.5	
Elias 3-18	20-01-05	CB	7	8.5	3.0			B5	
ITG 31	20-01-05	CB	7	8.5	3.0	9.1	5.2	K0	565
LkHA 332	21-01-05	CB	7	8.4	3.0	14.7	7.9	K5	
IRAS 04395+2521	21-01-05	CB	7	8.5	3.0		5.5		
04440885+2540333	21-01-05	CB	7	8.6	3.0		6.9		
05415664+2707323	22-01-05	CB	7	8.5	3.0				
SAO 78540	23-01-05	CB	7	8.6	3.0	6.9	5.3	G0	36
HD 283610	16-02-05	CB	7	8.5	3.0	9.6	5.4	K5III	
04264187+2500314	17-02-05	CB	7	8.4	3.0		6.7		
SAO 77000	17-02-05	CB	7	8.4	3.0	9.1	5.4	G5	244

Of course, the increase in the number of observed events is not reflected linearly in the number of results, such as the positive detection of field binaries, mainly because the majority of the events will be faint and offer limited dynamic range. We will return to this point in Sect. 4. The increase in the sheer number of observed events, on the other hand, implies a significant load of data inspection and analysis, particularly since data from IR arrays are substantially more demanding than those from photometers. This has prompted us to handle the bulk of raw data by means of automated processing. A new reduction pipeline was designed and implemented for the automated generation of preliminar lightcurve fits, which are then improved interactively. In particular, we concentrated our effort in two different areas. On one hand, we performed a comparative study of different algorithms of light curve extraction, such as aperture photometry, Gaussian profile fit, object detection based on segmentation analysis and subtraction of fixed number of faintest to brightest pixels. The latter was found to offer the best performance over the range of SNR present in our data sets, using 30 and 15 pixels for the extraction of the background and star signals, respectively. On the other hand, a new algorithm was developed to estimate automatically the lightcurves parameters (occultation time, stellar and background intensity). A particular wavelet transform of the lightcurve was chosen for this purpose, as it was capable of isolating the desired frequency signature while preserving the temporal information. The algorithm showed great robustness even in worst SNR conditions. This work will be described in detail in a separate paper.

The data were analyzed by means of various methods, as already described in Richichi et al. (2002, 2003) and references therein. The main engine for data analysis is based on a model-dependent least squares method (LSM). Free parameters include the stellar intensity, the rate of the event, the intensity of the background and its time drift. For single stars another parameter is the angular diameter, and additionally for binary stars the angular diameter of the companion, the projected separation and the brightness ratio are included. Spurious frequencies due to pick-up of mains power and other effects may be present occasionally, and can be digitally filtered. Relatively slow, random fluctuations of the background (due to thin cirrus and lunar halo) and of the stellar intensity (due to image motion and scintillation), can be fitted and accounted for by means of Legendre polynomials as described in the above mentioned papers. Another approach is to use a model-independent method (CAL, Richichi 1989), which is particularly suited for the detection or confirmation of companions at very small separations. This method is also of great advantage in cases when the source may not be

a simple circular disk, or in the presence of extended circumstellar emission.

3. Results

The stars for which a positive result could be obtained are listed in Table 4, using the same format already used in F04. In summary, the columns list the absolute value of the fitted linear rate of the event V, its deviation from the predicted rate V_t, the local lunar limb slope ψ, the position and contact angles, the signal–to–noise ratio (SNR). For binary detections, the projected separation and the brightness ratio are given, while for RZ Ari the angular diameter ϕ_{UD} is reported, under the assumption of a uniform stellar disc. All angular quantities are computed from the fitted rate of the event. Only in 2MASS 04264187 +2500314 we were not able to reliably fit a rate, due to the low SNR. For this source, the predicted values are listed in parentheses. Note that in the tables of this paper the 2MASS prefix is omitted.

3.1. SAO 164567

This star was revealed as a binary in a Calar Alto observation reported in F04. On the same night, the star was observed also from TIRGO. The binarity is clearly confirmed, but it is difficult to extract a true position angle from the combination of the value reported in F04 with that presented in Table 4. This is due partly to the relatively small difference in position angle predicted for the two sites (only 3°), and partly to the fact that the Calar Alto event was fitted with a speed that, in spite of just 2.9% excess over the predicted value, does not allow to compute unambiguously the exact position angle. This happens occasionally when a LO event has a very small contact angle.

We can only conclude that the companion is generally oriented towards the North, at a separation that could be significantly larger than the projected value of Table 4, up to ≈50 mas. Attempts to confirm the true position angle by techniques such as speckle interferometry are possible. From the two events we have reliable magnitude differences both in the R and the K bands. This permits us to infer that the secondary is bluer, by $R-K \approx 1.5$ mag, than the primary. The primary is classified as a K5 giant (Houk & Smith-Moore 1988), therefore we estimate that the secondary should have $R-K \approx 0.9$, which would be consistent with a late A or early F star.

3.2. SAO 110325

This newly detected binary was the subject of several previous observations by speckle interferometry (McAlister 1978, Hartkopf & McAlister 1984) as well as LO (Evans & Edwards 1981). The star was reported as unresolved also by Hipparcos. The fact that none of these previous records revealed the companion can be explained by the small projected separation that we list in Table 4, and possibly by the brightness ratio equivalent to $\Delta K = 2.8$ mag, which might be even larger at shorter wavelenghts.

3.3. SAO 165154

A LO event for this star was reported by Evans et al. (1985), who did not find evidence of binarity. We note that the star is relatively faint in the visual and the secondary might not have been detected previously for reasons of dynamic range.

3.4. RZ Ari

The bright, O-rich M6 star RZ Ari (45 Ari, ρ_2 Ari, HR 867) has been the subject of several investigations by high angular resolution methods. Five previously available angular diameter determinations are listed in the CHARM2 catalogue (Richichi et al. 2005). The results are somehow heterogeneous, including observations at various wavelengths in the optical and near-IR by LO and LBI, and referring to either uniform, partially or fully limb-darkened disk diameters (UD, LD, FD respectively).

The star is an irregular long-period variable, although the amplitude is relatively small (0.6 mag, Kukarkin et al. 1971). In the near-IR the amplitude of variability is not well documented, and it can be assumed to be even smaller. An examination of the data available from the AAVSO shows a slight trend of increasing luminosity by about 0.5 mag over the past 30 years in which diameter measurements are available. Neglecting in a first approximation significant changes of angular diameter due to variability, we plot all available determinations in Fig.1, using UD values. The conversion from LD and FD to UD has been done by using guidelines and conversion factors provided in the original references. The uncertainties in this conversion can be considered smaller than the error bars on the diameter determinations. It can be noted that there is a general agreement among the various determinations. A weighted mean yields the UD value 10.22 ± 0.12 mas.

No definite trend of the characteristic size with wavelength seems to be present, as would have been expected in the presence of circumstellar matter, due to scattering at shorter wavelengths and thermal emission at longer ones. Therefore we can conclude that circumstellar matter is not dominant. This is independently confirmed by mid-infrared spectra, that show a featurless continuum around 10μm (Speck et al. 2000). Also, there seems to be no evidence of binarity, a possibility which had initially been postulated on the basis of Hipparcos results. Percy et al. (2002) have discussed the origin of the problem with the Hipparcos data. Also speckle interferometry investigations by Mason et al. (1999) did not find companions. From our LO result, we can put an upper limit of ≈1:40 on the brightness ratio of a hypothetical companion with a projected separation in the range ±70 mas.

Table 4. Summary of results

(1) Source	(2) $\lvert V \rvert$ (m/ms)	(3) V/V_t–1	(4) ψ(°)	(5) PA(°)	(6) CA(°)	(7) SNR	(8) Sep. (mas)	(9) Br. Ratio	(10) ϕ_{UD} (mas)
SAO 164567	0.7325	3%	7	78	14	49.2	8.4 ± 0.2	6.8 ± 0.2	
SAO 110325	0.8571	−0%	−1	59	−7	37.0	7.8 ± 0.8	13.4 ± 1.1	
SAO 80764	0.6568	−3%	−2	73	−45	26.3	42.5 ± 0.3	14.9 ± 0.3	
SAO 185661	0.3287	−5%	−2	155	60	23.7	37.9 ± 1.1	19.3 ± 0.7	
IRC -30319 A-B	0.5647	3%	2	136	44	52.6	15.0 ± 0.1	8.74 ± 0.04	
IRC -30319 B-C						16.1	21.8 ± 0.1	1.98 ± 0.01	
17454891-2809333	0.7720	4%	3	98	6	25.0	39.3 ± 0.7	17.3 ± 0.9	
SAO 165154	0.5870	24%	14	117	62	6.2	43.0 ± 1.9	4.7 ± 0.4	
RZ Ari	0.6520	−2%	10	73	11	41.3			10.6 ± 0.2
SAO 76214 A-C	0.3500	−5%	−2	131	56	7.8	13.0 ± 0.7	2.4 ± 0.1	
IRAS 04395+2521	0.6301	11%	8	135	49	21.4	6.5 ± 0.2	2.9 ± 0.1	
04440885+2540333	0.8013	−0%	−0	77	−10	3.9	15.6 ± 0.8	1.4 ± 0.1	
05415664+2707323	0.9208	−2%	−3	108	12	17.4	24.8 ± 0.3	7.8 ± 0.3	
HD 283610	0.5244	−5%	−3	121	38	9.1	19.4 ± 0.7	6.1 ± 0.3	
04264187+2500314	(0.8900)	–	–	(86)	(0)	3.8	89.5 ± 1.0	2.5 ± 0.1	
SAO 77000	0.4995	2%	−2	109	37	16.0	12.6 ± 0.3	1.49 ± 0.03	

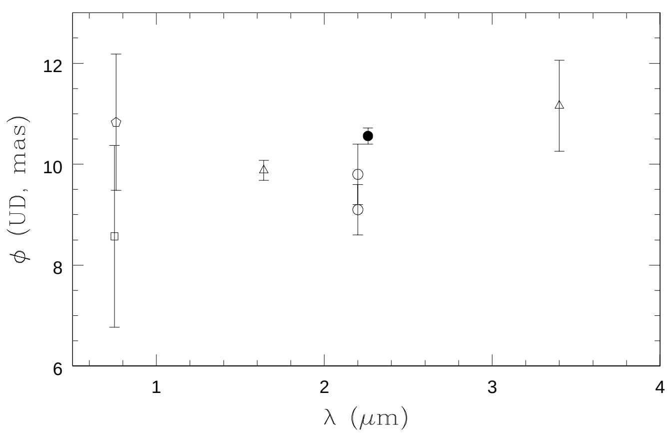

Fig. 1. Angular diameter determinations for RZ Ari. The filled circle is our result, while the open symbols are: square Africano et al. (1975), pentagon Beavers et al. (1981), triangles Ridgway et al. (1980), circles Dyck et al. (1998).

RZ Ari has been used as a building block in several empirical T_{eff} calibrations, such as those by Barnes (1976, 1978), Ridgway et al. (1980), Di Benedetto (1993). Dyck et al. (1998) provided a revised value of the bolometric flux, and using their own LBI diameter derived $T_{eff} = 3442 \pm 148$ K. Of course, diameter variations must exist in this star, and therefore it seems of secondary importance at this point to discuss the accuracy of the various determinations and to refine the T_{eff} value. It would be more important to follow diameter and temperature variations with a dedicate monitoring, a possibility which is made available by several of the current interferometers.

3.5. SAO 76214

Although this star is a known binary (Mason et al. 2001b), our detection corresponds to a new component, with the characteristics listed in Table 4. We detect also the previously known component in our LO event record, with a separation consistent with PA=270° and separation $0\farcs5$ listed by Mason et al. (2001b), but it is outside the scope of our observations to deal with such wide components. Moreover, the quantitative evaluation of the trace for SAO 76214 is hampered, especially on long time scales, by significant scintillation. We estimate the brightness ratio between the B and the A-C components to be 0.56 ± 0.10 in the K band. It is interesting to note that the Tycho Double Star Catalogue (Fabricius et al. 2002) examined this pair and found a ΔV=2.59, however, LO (Africano et al. (1975) and visual estimates (most recently, Worley 1989) find a much smaller value, $\Delta V \approx 0.3$.

3.6. SAO 77000

This star has been repeatedly observed by filar micrometry (Couteau 1972, 1975, 1979, 1987, 1989, Heintz 1980) as well as by Hipparcos. Orbital motion is apparent over the period of 20 years spanned by the observations, however no clear orbital trend can be deduced yet. Due also to the intrinsically larger errors associated with visual observations, it is hard to extrapolate a possible position of the component for the epoch of our LO event (2005.13). Nevertheless we note a general consistency of quadrant and magnitude of the separation. Our measurement provides a significant constraint, since it follows about 14 years after the most recent available measurement. Assuming to a first approximation that the magnitude difference observed by Hipparcos (ΔHp=0.58 mag) is similar to that in the V band, the comparison with the K band brightness ratio provided in Table 4 indicates that the two components have almost the same color, i.e. similar spectral types.

3.7. Other binaries

The remaining stars listed in Table 4 have no previous report of binary detection. Among these, the following objects have at least one bibliographical entry present in the *Simbad* database: SAO 80764, SAO 185661, the triple star IRC -30319, IRAS 04395+2521, and HD 283610. However these publications are on subjects not related to high angular resolution observations. There are no known previous publications associated with the four 2MASS objects present in Table 4.

We also mention that we have detected binarity in three further stars from Table 2, namely SAO 109617, SAO 110089 and SAO 78540. These are relatively wide systems, with separations of order $0\farcs5$, and therefore easily accessible to standard observations. For this reason, and also because LO are not very accurate for such large separations due to possible differences in local limb slope for the two components, we have not included these results in Table 4. However, we consider it possibly useful to report the brightness ratios in the K band. The values are 1.26 ± 0.02, 1.70 ± 0.03 and 0.5 ± 0.1, in the above order. It is noteworthy that all three stars have been measured at visual wavelengths by speckle interferometry and/or by Hipparcos. We quote, among others, Δm values of 1.66 mag (G band, Balega et al. 2004) and 1.87 mag (Hp band, Fabricius & Makarov 2000) for SAO 109617, and ΔHp values of 0.49 mag and 1.73 mag for SAO 110089 and SAO 78540, respectively (Fabricius & Makarov 2000). We note that these latter authors provide also Tycho B and V magnitude differences. We do not speculate at this point on the combination of all these values with our K-band determination, in view of the diversity of spectral bandpasses used in the visual.

A number of stars from Table 5 are additionally wide binaries with separations of several arcseconds, and we do not concern ourselves with them here.

3.8. Other stars of interest

Among the stars for which we did not detect binarity, a few are worthy some comments either because of their nature or because of previous attempts by high angular resolution techniques. SAO 80310 was investigated by Mason et al. (2001a) by speckle interferometry, with negative conclusions. The same result with the same technique was reported by Hartkopf & McAlister (1984) for SAO 92659. Both these stars were also found unresolved by Hipparcos.

SAO 164601 is a spectroscopic binary, which was previously observed as double by Evans et al. (1986). These authors reported a separation close to 1 mas, although without information on the brightness ratio. We have analyzed our trace (SNR=18.7) with both the LSM and CAL methods, without finding evidence of binarity. In any case, due to the near-IR wavelength and the relatively slow sampling, we are insensitive to separations of less than about 3.5 mas on this trace. We notice that the position angle of our event (110°) was almost orthogonal with that of the event observed by Evans and collaborators.

We also recorded occultations during the passage of the Moon over two regions of special interest. On July 28th, 2004 the Moon reached a minimum distance of $0\fdg59$ from the Galactic Center. In this crowded, heavily obscured region we could record 54 events at the 2.2 m telescope in 3.4 hours, being limited by overheads in telescope pointing and data storing. The majority (50) of the objects has no counterpart in optical catalogues. Spectral types on the other hand are known for about half the sample, thanks mostly to the work of Raharto et al. (1984). With very few exceptions, the stars are all of M spectral type. From the photometry available in the 2MASS catalogue (Cutri et al. 2003), it can be observed that about half of the stars have a color $J-K>1$, indicating significant reddening. This is presumably due to interstellar dust in the direction of the Galactic Center, however in some cases colors as red as $J-K=3.5$-5.0 are present, possibly pointing to additional circumstellar extinction.

In January 2005, we were able to record a passage of the Moon over the Taurus star-forming region. These passages are relatively frequent, and have been used in the past especially to derive important insights on the frequency of binaries in the early stages of stellar evolution (see Simon et al. 1995, and references therein). In our case, included were the following known young stellar objects: LH 98-106, DL Tau, GN Tau, Elias 3-18, ITG 31, LkHA 332. A few IR sources without optical counterpart were also recorded. Unfortunately, the sensitivity offered by the 1.5 m telescope was not sufficient to obtain quantitative results. Details on the full sample of occulted objects can be found in Table 5, available only on-line.

4. Considerations on performance and statistics

In F04 we reported the limiting sensitivity computed for LO observations with the MAGIC instrument. It was shown that the logarithm of the SNR of a LO light curve is approximately in inverse linear relation to the K magnitude. At the 1.5 m telescope, with the typical integration and sampling times of 3 and ≈8 ms respectively, it can be expected to detect objects having $K \approx 8$ mag with SNR=3. The present sample is much larger than that of F04. Excluding the sources observed from TIRGO (since those observations employed an entirely different detector and a comprehensive statistics for that configuration was already provided by Richichi et al. 1996), RZ Ari which was observed with a narrow-band filter, and a number of sources which were deemed too faint and plainly not binary and consequently without a detailed analysis, we are left with 285 events. However, the SNR-K relationship of the present sample is not straighforward to interpret. Firstly, about 20% of the stars were observed with the 2.2 m telescope and show a trend which is offset from the main relationship by the expected factor of mirror area. Secondly, about 2/3 of the runs at the 1.5 m telescope were carried out with a wrong position of the pupil wheel which

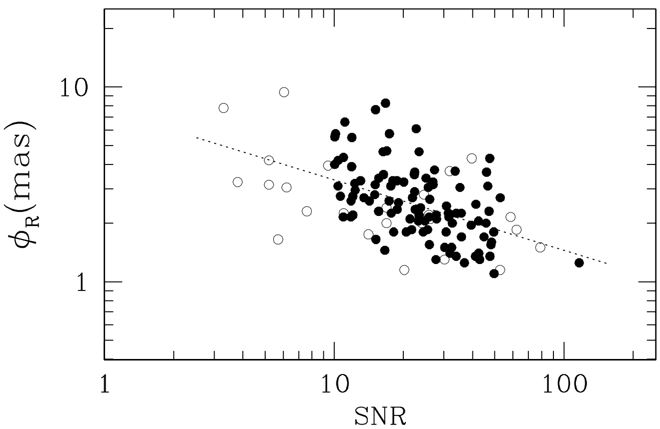

Fig. 2. Limiting resolution for the sources in our sample, as a function of SNR (solid dots). Only points with SNR>10 are included. Also shown as open circles are the determinations from Fors et al. (2004). The solid line is a log-log fit through all points.

holds the cold stop. This had no effect on the stellar signal, but has produced a large increase in thermal background, resulting in higher noise, resulting in lower SNR than expected for a given stellar magnitude. As a consequence our sample is more inhomogeneous than that of F04, although the general characteristics of the relationship are confirmed. At the 1.5 m telescope we recorded about 20 events for stars with K between 8 and 8.5 mag. At the 2.2 m telescope, used only for the very crowded passage near the Galactic Center, we had a sufficient number of bright sources and the real limiting magnitude was not reached.

Similarly to what was done in F04, we have computed also the limiting angular resolution associated with the unresolved sources, following the same approach of Richichi et al. (1996). This has been done for 103 stars in our sample having SNR>10, or about 4 times more numerous than in the sample of F04. The result, including a comparison with this latter work, is shown in Fig. 2.

It can be noted that the current sample and the previous from F04 have an almost identical distribution of limiting resolution against SNR, and can be fitted by the same log-log relationship. This is reassuring, since the behaviour be independent of the source, and be determined by the instrumental characteristics and in particular by the integration time. The large spread in the relationship can be understood in terms of large variations of SNR from one LO light curve to another due to different situations of background and also to the specific conditions of signal extraction from the discrete pixels of the detector. Broadly speaking, the average relationship is such that SNR=10 ensures a limiting resolution of about 3 mas. In the few cases in which SNR close to 100 could be recorded, the limiting resolution improves but remains above, as already noted in F04, the performance of fast InSb photometers which can operate with faster sampling.

A final consideration can be made about the statistics of binary detections in our sample. We have observed a total of 14 binaries (counting as such also the triple star IRC -30319), out of a total sample size of 350 stars. This points to a fraction of 4.0%, or more than two times smaller than what observed by Richichi et al. (1996) and in F04. This result seemed puzzling at first, since all the samples considered have a broad sky distribution and should have similar characteristics. It is not excluded that the targets that we observed in the direction of the Galactic Center have an actual deficit of binaries, due to the fact extinction introduced a bias towards stars that for a given apparent magnitude are more distant than in the previous samples. Therefore, hypothetical companions would have smaller angular separations for the same statistics of semi-major axis. However, only 20% of the stars in our sample were observed in the direction of the Galactic Center, and another explanation must exist for the lower binary fraction that we observe in the present work.

In fact we note that with the introduction of large, deep IR catalogues such as 2MASS in our predictions, we have effectively shifted the distribution of K magnitudes in our sample much closer to the limiting sensitivity of the technique. Therefore, we can expect that most of the LO light curves will have on average lower SNR than in the previous samples. As a result, it will become effectively more difficult to detect companions, especially those with brightness ratios larger than unity. Although we have not performed a detailed computation of this effect, its magnitude could easily explain the observed apparent deficit of binary detections. We conclude that the introduction of large catalogues, while increasing the number of predictions and correspondingly of observed LO, does not automatically produce a higher rate of results.

5. Conclusions

We have provided an update on the program of lunar occultation observations which is operational at Calar Alto Observatory, previously described by Fors et al. (2004), including 350 lunar occultation events. Although no major changes have occurred with respect to instrumentation, the program has been expanded to include, in addition to the Spanish 1.5 m telescope, also the 2.2 m telescope. Additionally, we have developed and made use of new methods of light curve extraction and characterization, suitable to perform in an automated fashion the preliminary analysis of large volumes of lunar occultation data. This has been made necessary by the availability of large, deep near-IR catalogues such as the 2MASS (Cutri et al. 2003) and DENIS (Paturel et al. 2003), which permit the prediction and observation of a much increased number of occultation events.

The results include the detection in the near-IR of one triple and 13 binary systems. For all but two stars, these represent first time detections. Projected separations range from 0$''$.09 to 0$''$.007, and brightess ratios reach up to 1:20 in the K band. We have also determined the an-

gular diameter of the M6 star RZ Ari, which we have discussed in comparison with previous determinations. Our observations have included a passage of the Moon over a crowded region in the vicinity of the Galactic Center (resulting in 54 events observed in about 3 hours), and a passage in the Taurus star-forming region. Passages of the Moon close to the Galactic center are taking place in these years, and we have provided some examples. These events provide a unique opportunity to extract milliarcsecond resolution information on a large number of objects in obscured, crowded and relatively unstudied regions, and can be adequately observed with 2-4 m -class telescopes.

We have discussed the performance achieved in our observations in terms of limiting magnitude and angular resolution. We have shown that at 1-2 m class telescopes equipped with a rather traditional array detector it is possible to achieve $\approx 0\farcs003$ on sources as faint as $K \approx 8$ mag. The rate of binary detection in random observations of field stars that emerges from the present work is $\approx 4\%$, considerably lower than established earlier by similar studies (Richichi et al. 1996, Fors et al. 2004). We attribute this effect largely to the fact that the use of catalogues such as 2MASS has increased dramatically the number of occultation observable per night, but this increase is realized mostly at the faint magnitude end, where the dynamic range available is much smaller than for brighter stars.

Acknowledgements. We thank the Observatorio Astronómico Nacional (OAN) and Centro Astronómico Hispano-Aleman (CAHA) for the facilities and support made available at Calar Alto, and in particular Santos Pedraz (CAHA) for his invaluable help on many occasions. This publication makes use of data products from the *Two Micron All Sky Survey*, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation. We acknowledge with thanks the variable star observations from the AAVSO International Database contributed by observers worldwide and used in this research. This research has made use of the *Simbad* database, operated at CDS, Strasbourg (France), and of the Washington Double Star Catalog maintained at the U.S. Naval Observatory. The paper has been improved by several detailed references provided by the referee, Dr. B. Mason.

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